Sensitivity limits of atom interferometry gravity gradiometers and strainmeters

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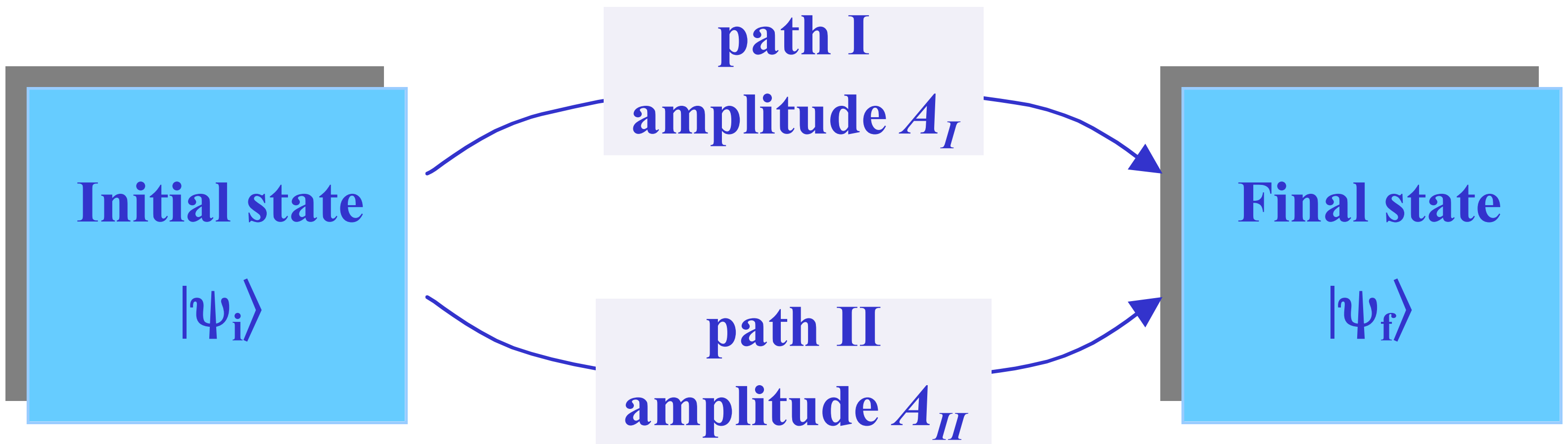
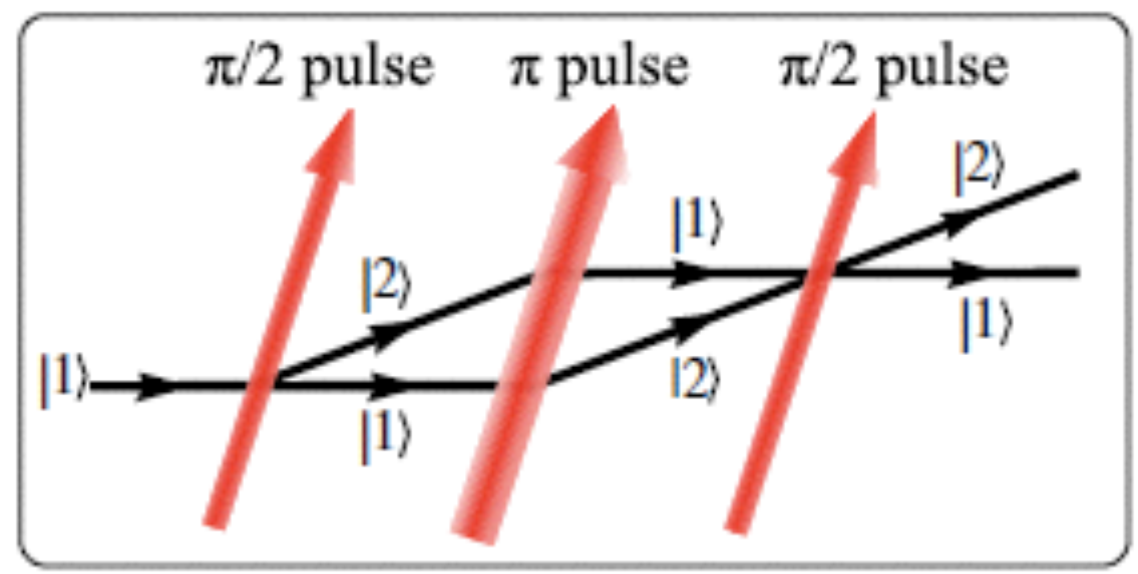
Outline

- AI sensors, state of the art performance
- Main noise sources
- Potential improvements
- Technology readiness of AI sensors for field use

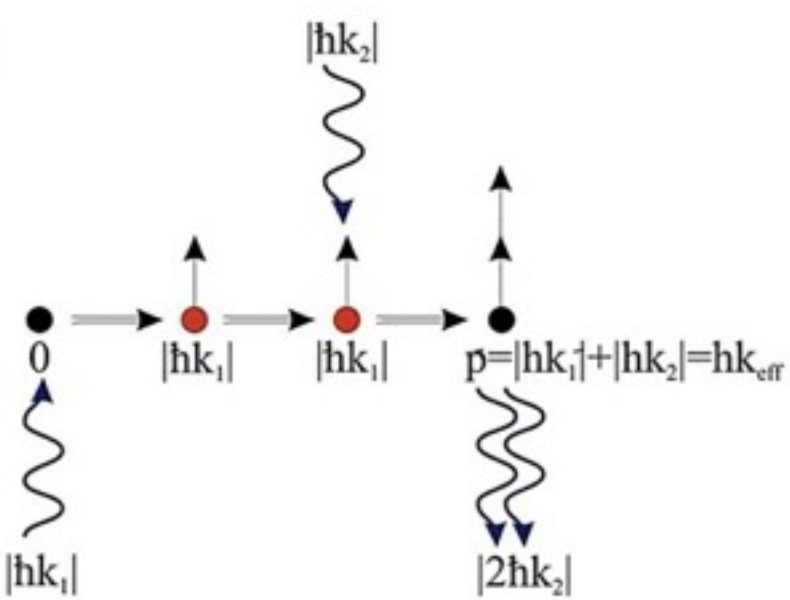
Atom interferometry

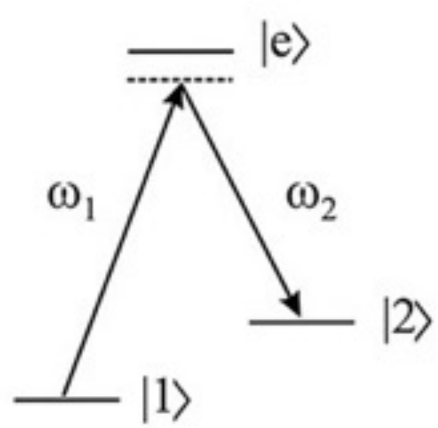


Interference of de Broglie amplitudes



Light-pulse beam splitters + fluorescence detection



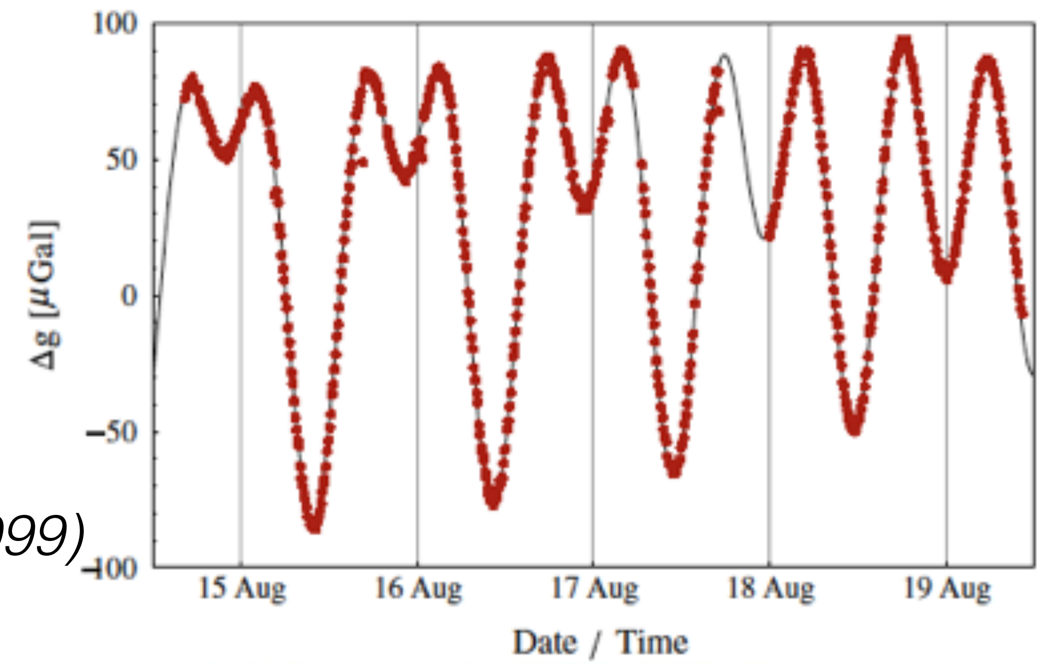


Output phase selectively sensitive to different effects (inertial, gravitational, external fields, laser phase/frequency, etc) via choice of quantum states

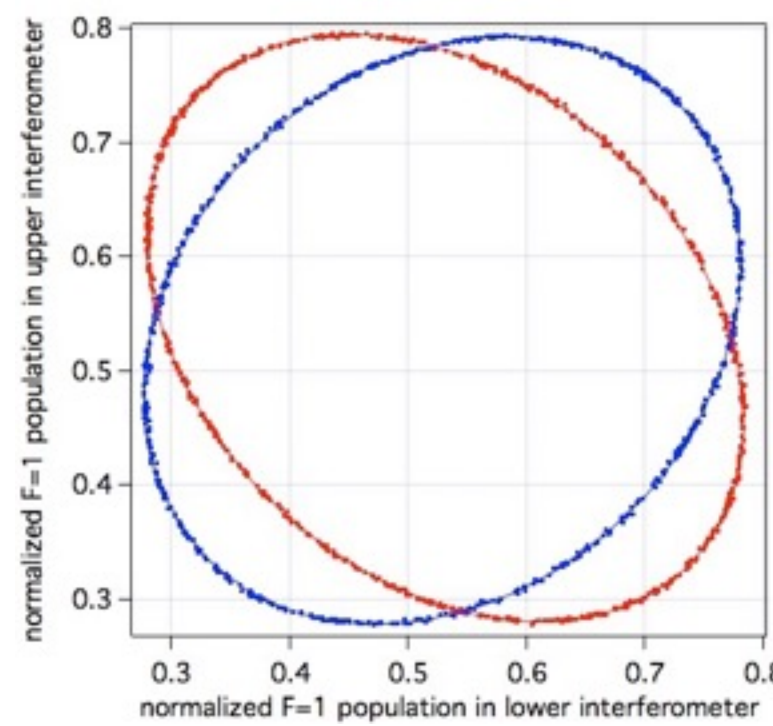
AI & low frequency GW

- AI inertial sensors feature very good long term stability and control over systematic effects
  - might provide complementary technologies for <Hz GW detectors
- Gravity gradiometers
  - measurement/correction of NN
- Strain meters
  - free fall: vibration isolation without suspensions
  - quantum interaction of light with test mass
    - no radiation pressure noise
  - vertical orientation
- Rotation sensors

Current performance



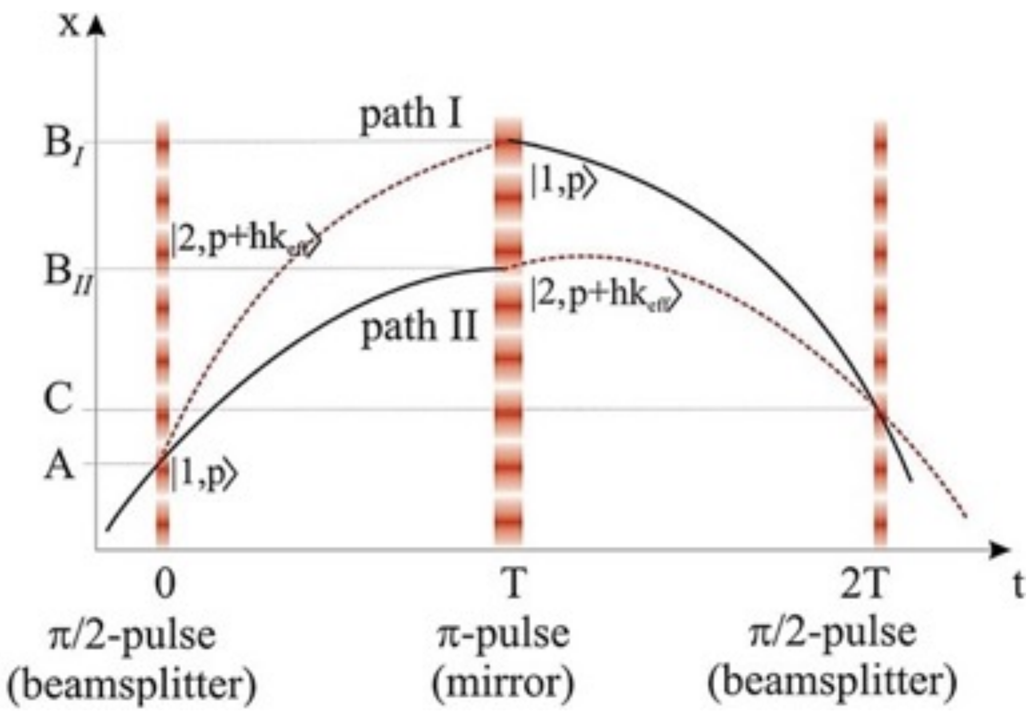
- Gravimeters
  - resolution: 3×10^{-9} g in 1 second (SYRTE)
  - averaging down to 2×10^{-10} g after 30 min (SYRTE)
  - accuracy: $10^{-9}\div10^{-10}$ g, limited by tidal models
    - *A. Peters, K.Y. Chung and S. Chu, Nature 400, 849 (1999)*
    - *H. Müller et al., Phys. Rev. Lett 100, 031101 (2008)*
    - *M. Hauth et el., Appl. Phys. B 113, 49 (2013)*
    - *P. Gillot et al., Metrologia 51, L15 (2014)*
- Gravity gradiometers
  - differential acceleration sensitivity: 5×10^{-9} g in1 s
  - 5×10^{-11} g after 10^4 s
    - *F. Sorrentino et al., Phys. Rev. A 89, 023607 (2014)*
- Rotation sensors
  - sensitivity: 6×10^{-10} rad/s/√Hz
  - scale factor stability <5 ppm
  - bias stability <70 μdeg/h
    - *T. L. Gustavson, A. Landragin and M.A. Kasevich, Class. Quantum Grav. 17, 2385 (2000)*
    - *D. S. Durfee, Y. K. Shaham, M.A. Kasevich, Phys. Rev. Lett. 97, 240801 (2006)*



Sensitivity limits

- Quantum noise
- Acceleration noise
- Laser wavefront
- Atomic motion
- Laser phase and frequency noise
- Aliasing
- External fields
- Other technical noise sources
- NN

Quantum projection noise



Phase difference between the paths:

$$\Delta\Phi = k_e[z(0) - 2z(T) + z(1T)] + \Phi_e$$

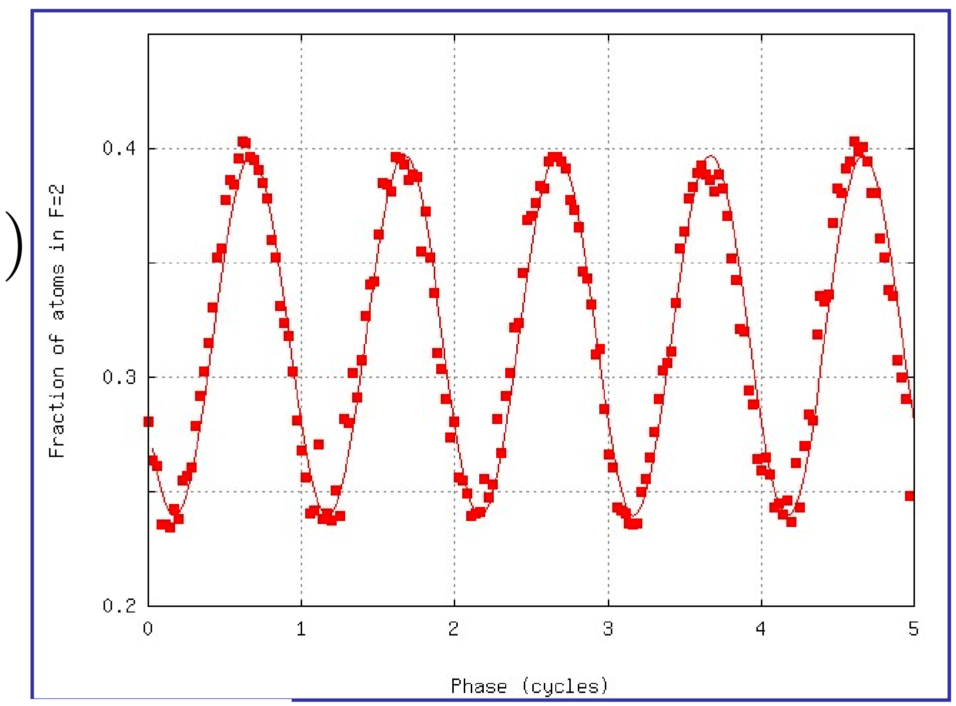
$$k_e = k_1 - k_2$$

with $z(t) = -gt^2/2 + v_0 t + z_0$ & $\Phi_e = 0$

$$\rightarrow \Delta\Phi = k_e g T^2$$

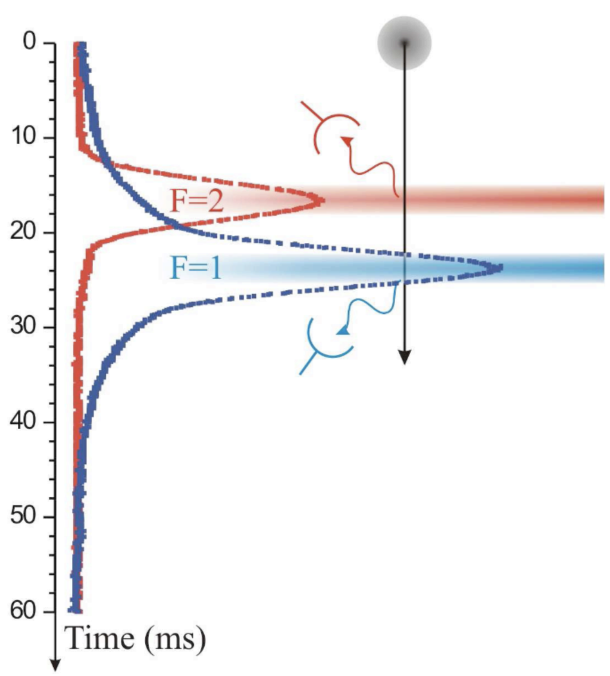
Final population:

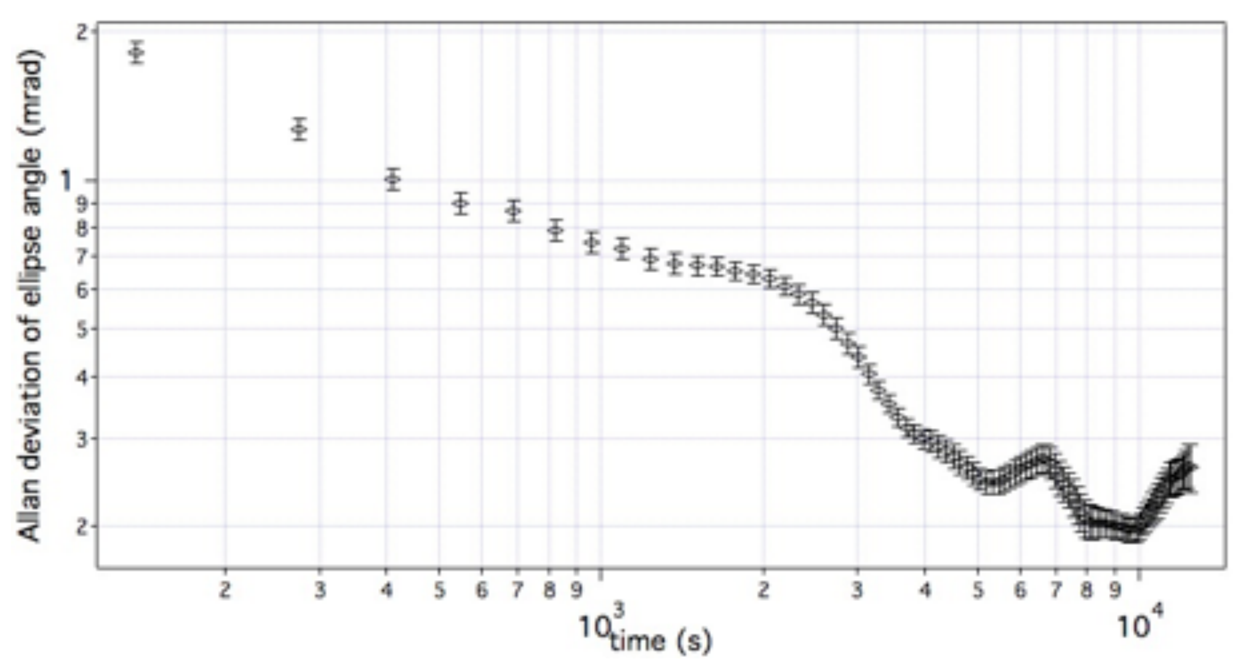
$$N_a = N/2(1 + cos[\Delta\Phi])$$



$T = 150$ ms $\rightarrow 2\pi = 10^{-6}$ g

S/N=1000 $\rightarrow$ Sensitivity 10^{-9} g/shot





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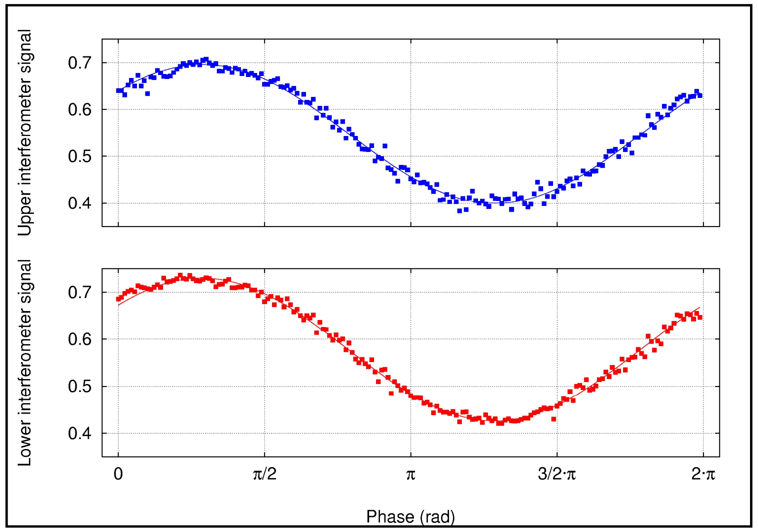
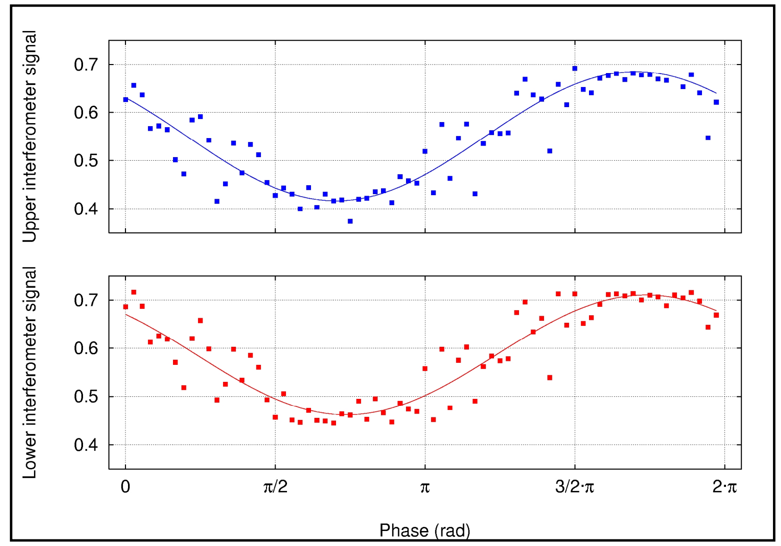
Sensitivity limits…

Acceleration noise



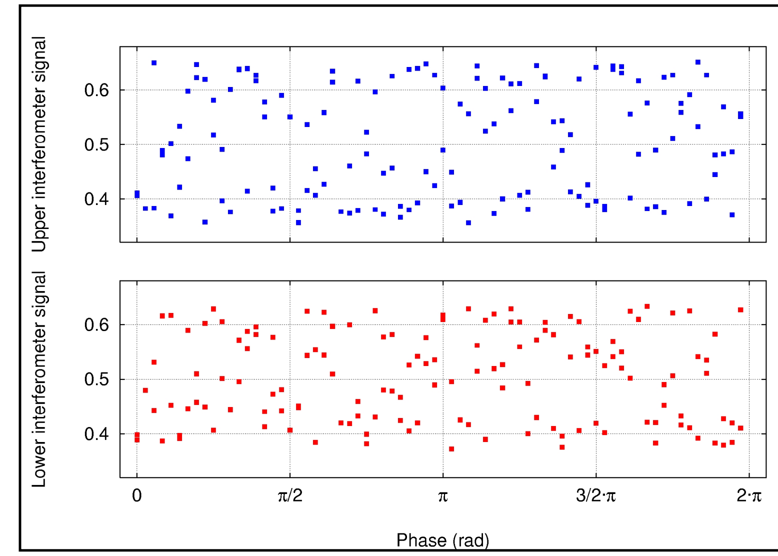
T=5 ms

resol. $= 2.3 \times 10^{-5}$g/shot



T=50 ms

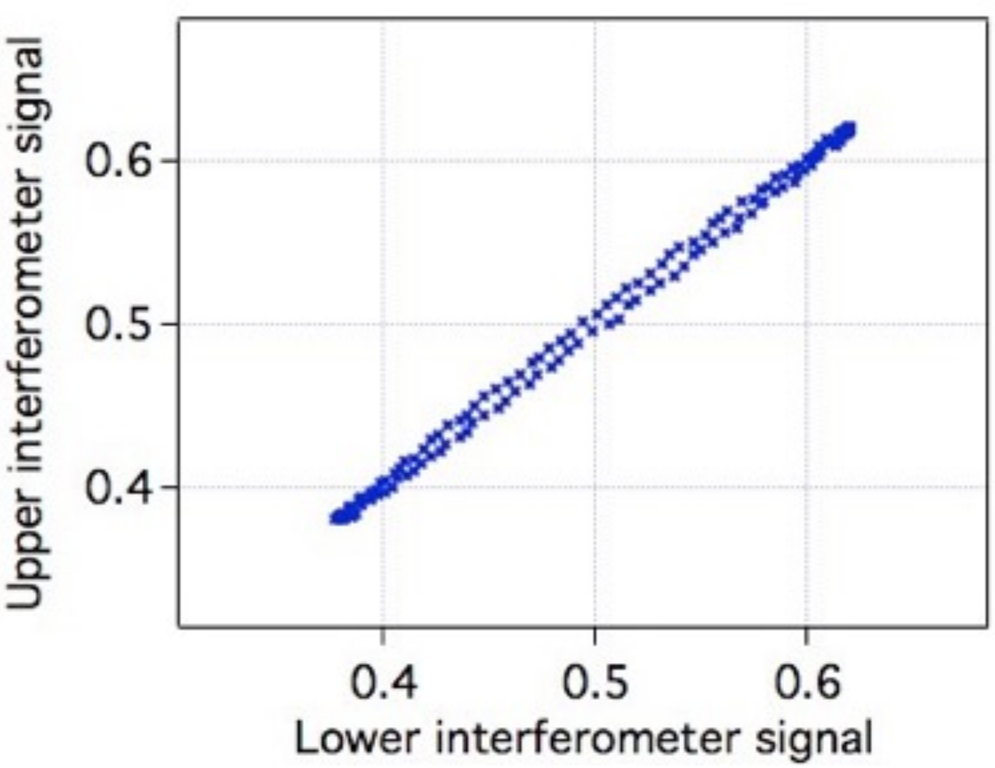
resol. $= 1.0 \times 10^{-6}$g/shot

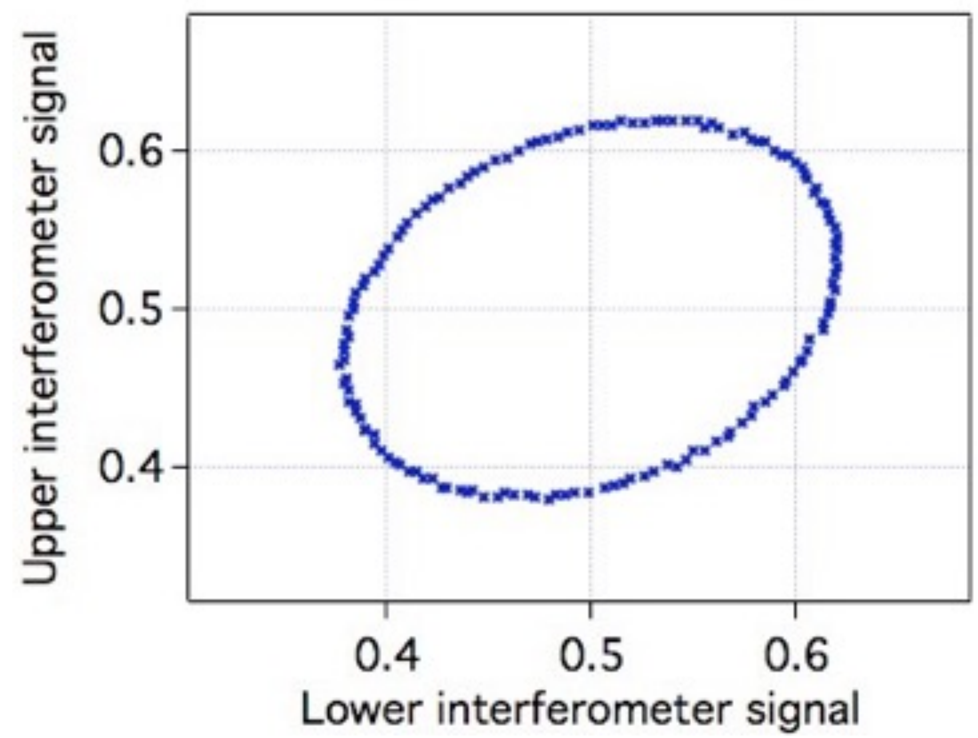


T=150 ms

resol. $= 3.2 \times 10^{-8}$g/shot

$$\Delta\Phi = k_e g T^2$$



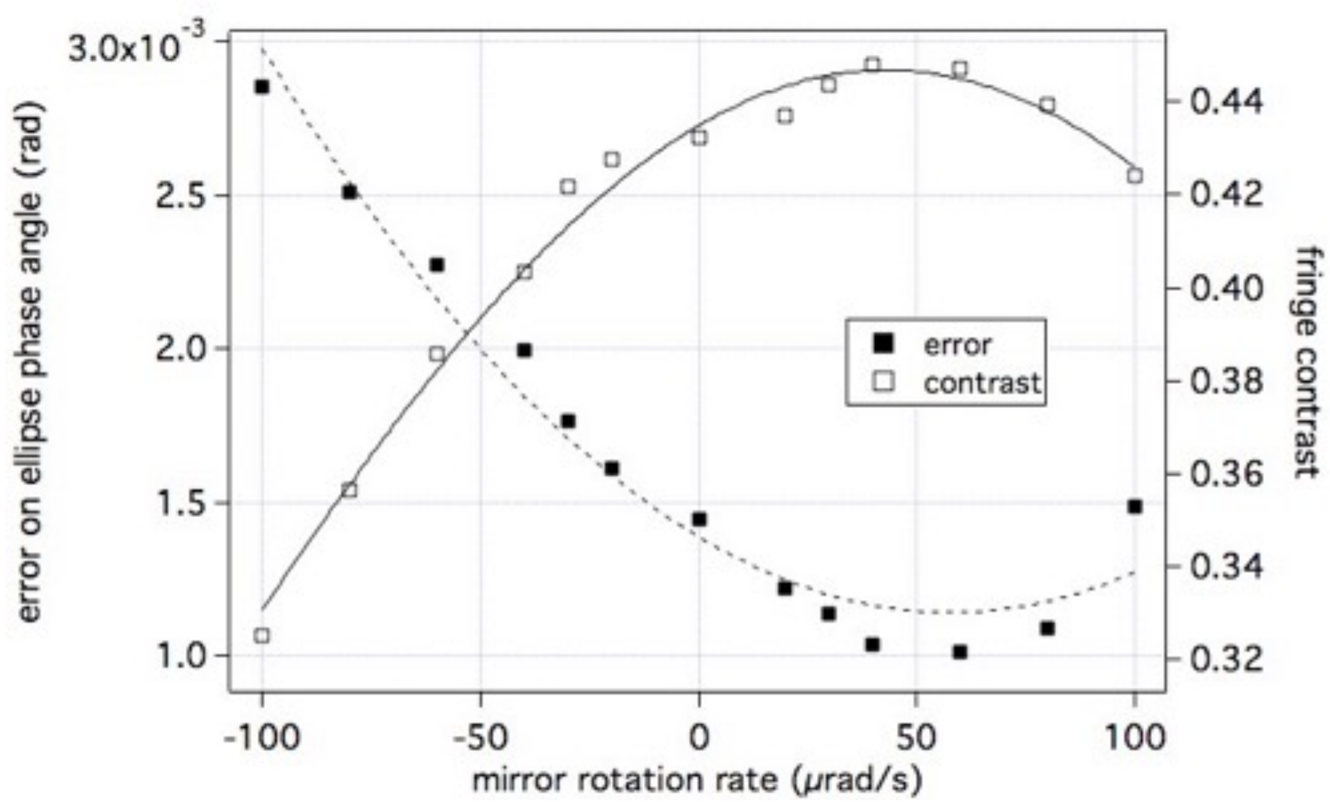


up to 140 dB CMRR with 1 m separation

G. T. Foster et al., Opt. Lett ***27***, *951 (2002)*

Atomic motion

- AI phase is affected by residual atomic motion
- Velocity spread due to finite temperature
- Shot to shot jitter in initial position and mean velocity
- Atomic motion couples with
  - laser wavefront distribution
  - Coriolis acceleration & higher order inertial effects
  - gravitational and magnetic gradients
- Coupled constraints on atomic temperature, launching velocity, and wavefront jitter
- Limits are particularly stringent for very long baseline (space GW detectors)
- For ground applications, nK temperatures and lambda/100 wavefront errors would be ok

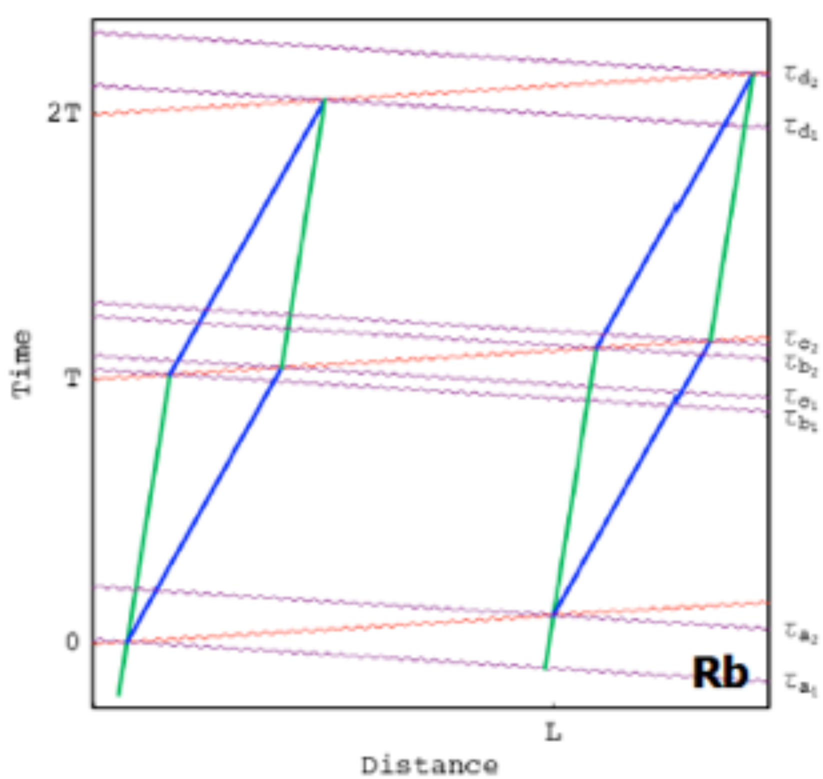


Laser frequency noise

- Simultaneous AI sensors (gradiometer, strain meter) sharing the same atom optics provide excellent CMRR for phase noise of laser field
- However, for long baseline the differential measurement is affected by common mode laser frequency noise due to high propagation delay
- Requirements on laser frequency noise are dramatically released if the beam splitters are driven by one-photon transitions (e.g. Sr clock transition @ 689 nm)
  - N. Yu and M. Tinto, Gen Relativ Gravit (2011) 43:1943 (2011)
  - P. W. Graham et al., PRL 171102 (2013)

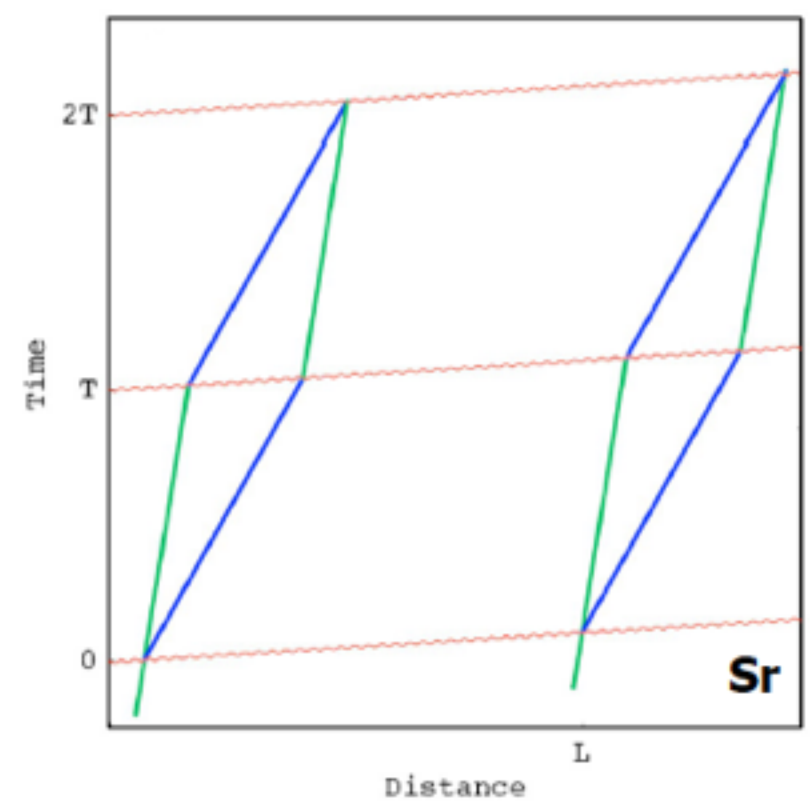
$$\sigma^2 \simeq 4\frac{\pi^4}{\tau}\frac{d^2}{c^2}S_\nu$$

2-photon transitions



GW signal from relative positions of atom ensembles with respect to optical phase fronts.

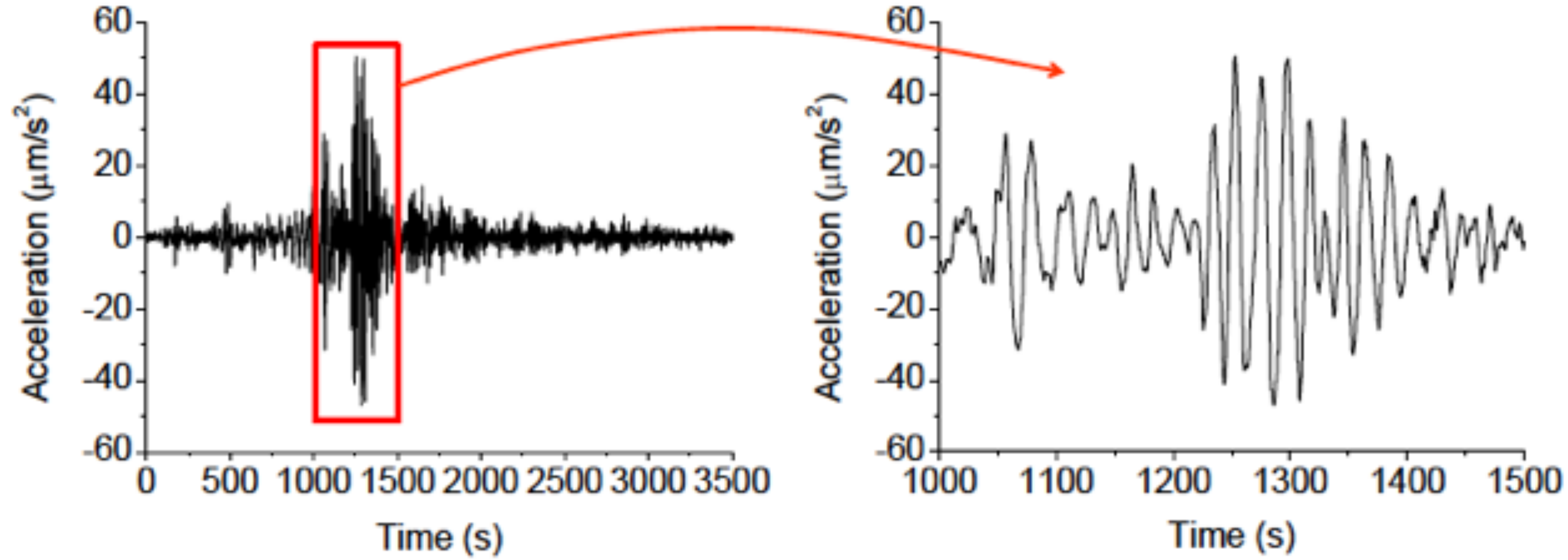
1 photon transitions



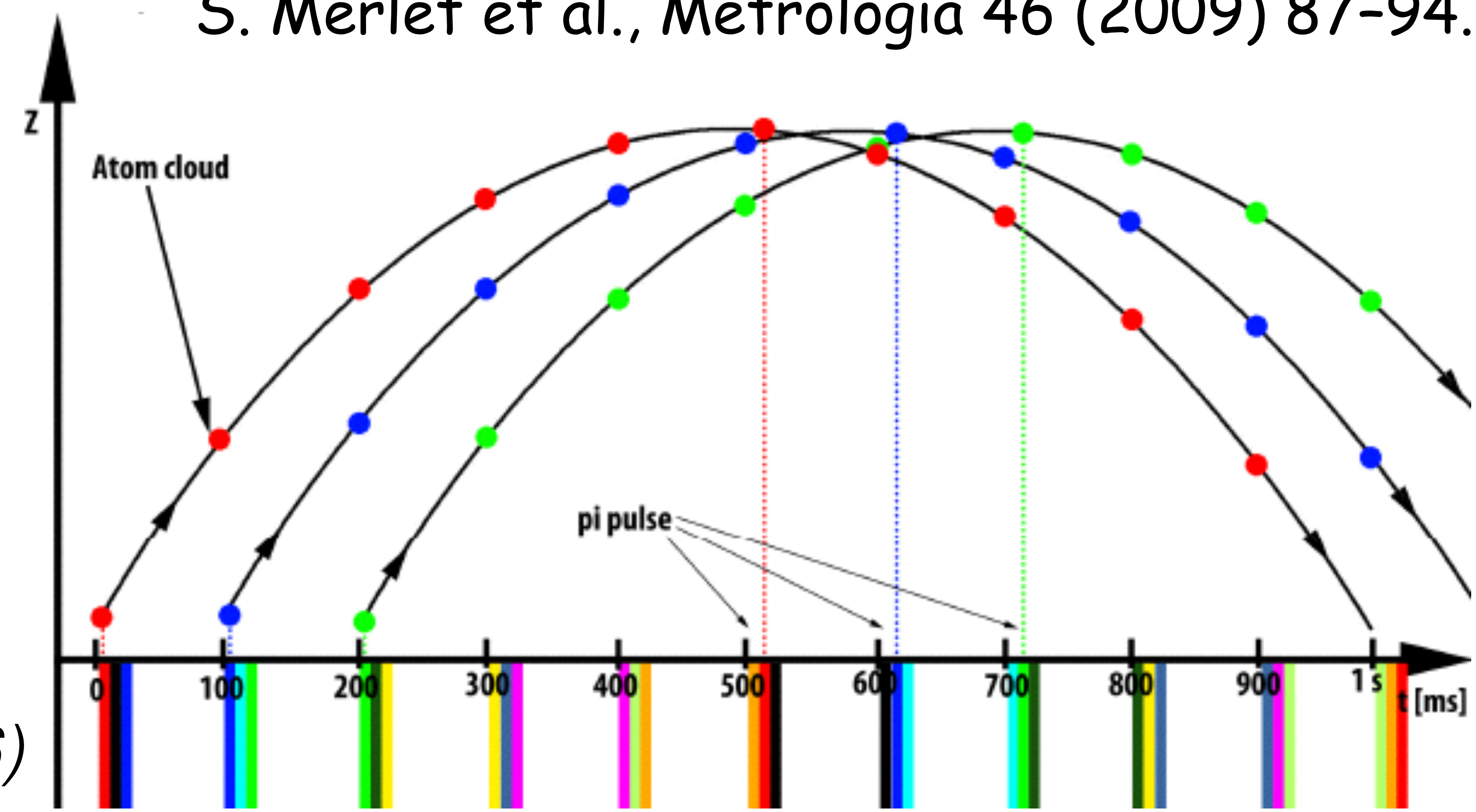
GW signal from light propagation time between atom ensembles.

Bandwidth & aliasing

- Sensitivity ~ T^2
- Bandwidth ~ T^{-1}
- Highly sensitive gravimeters detect earthquakes
  - T~50 ms
  - rep rate ~ 5 Hz
- Improving T without loosing bandwidth
  - interleaved interferometers
  - main limit: Doppler separation of different channels
  - see e.g. *I. Dutta et al., PRL 116,183003 (2016)*



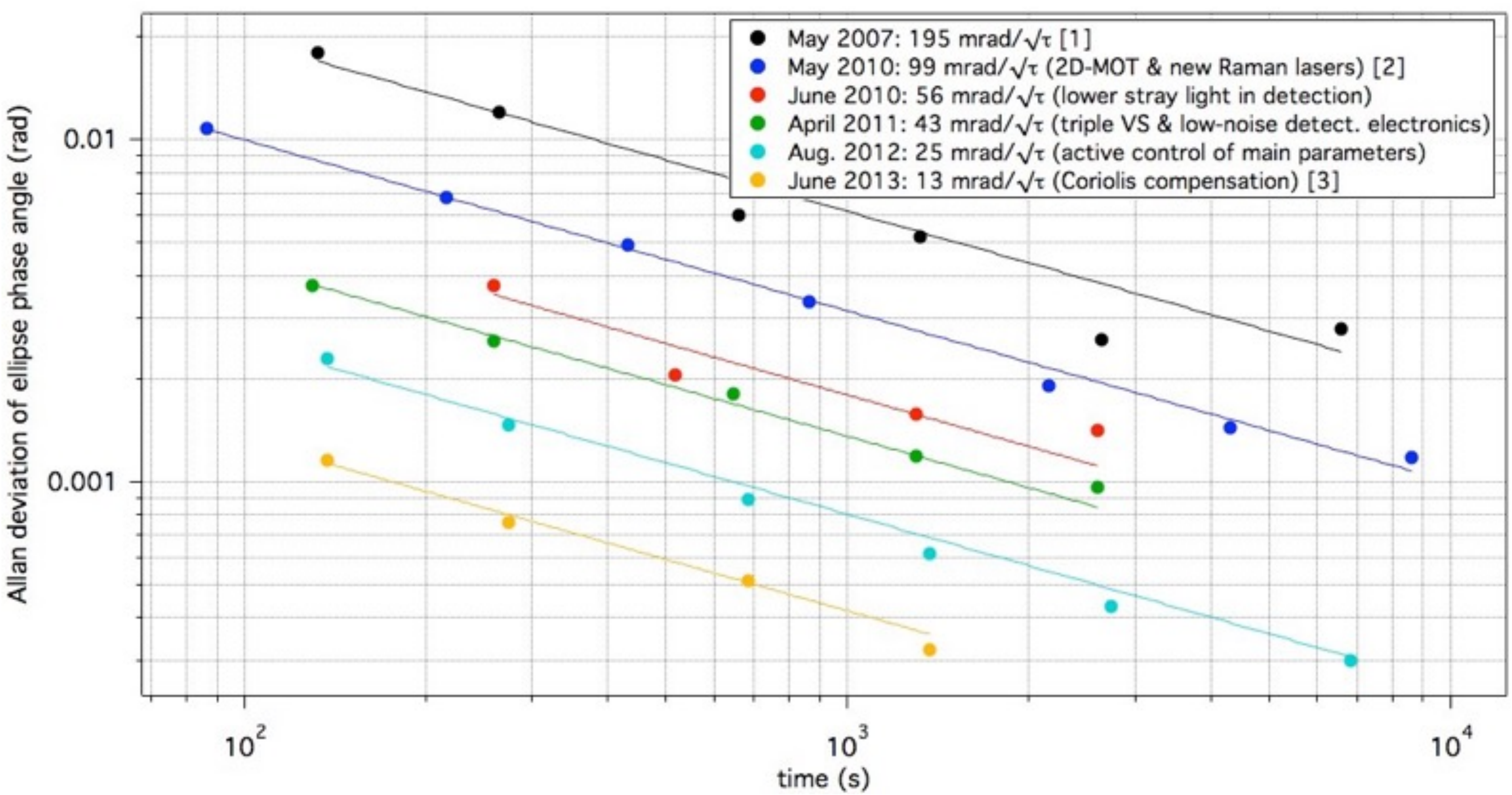
S. Merlet et al., Metrologia 46 (2009) 87-94.



Technical noise sources

- magnetic fields
- stray light
- photon shot noise
- tilt noise

[1] G. Lamporesi et al., Phys. Rev. Lett 100, 050801 (2008)
[2] F. Sorrentino et al., New J. Phys. 12, 095009 (2010)
[3] F. Sorrentino et al., Phys. Rev. A 89, 023607 (2014)



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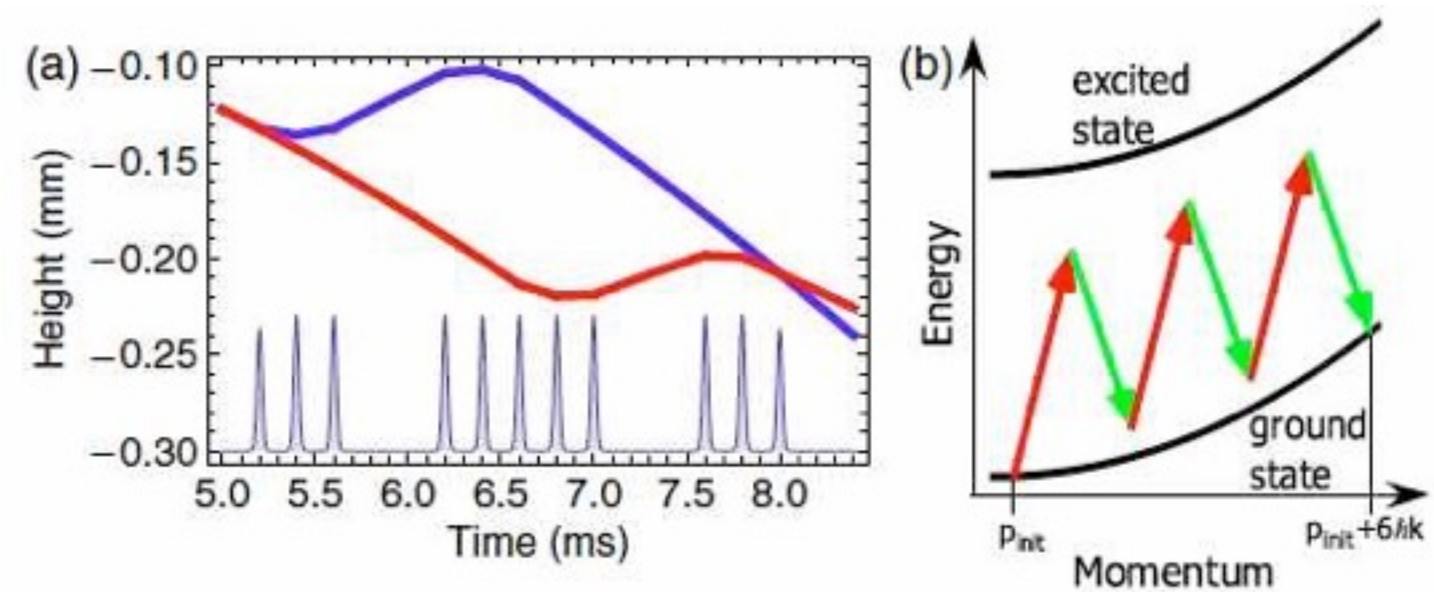
Potential improvements

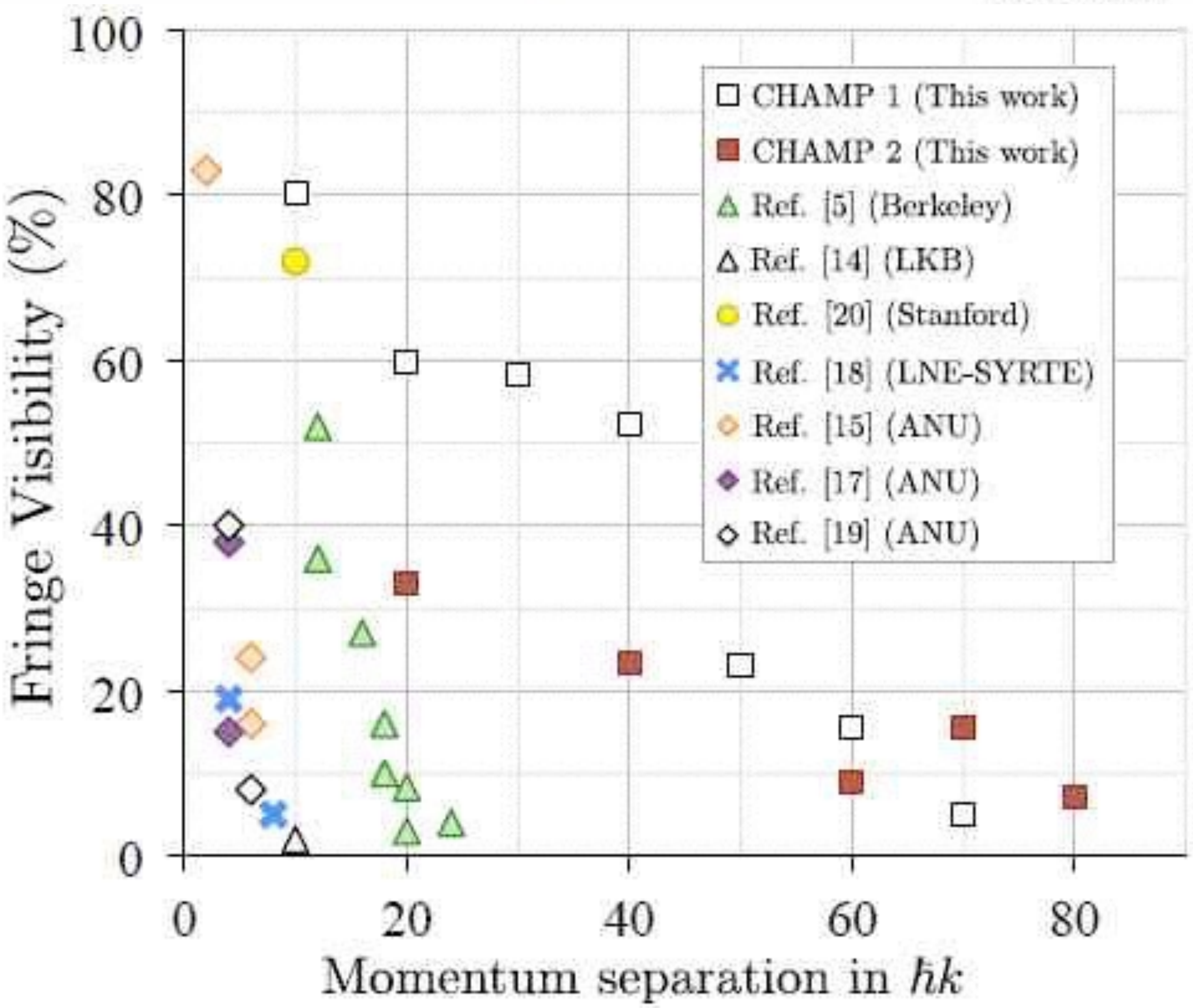
$$\Delta\Phi = nkgT^2$$

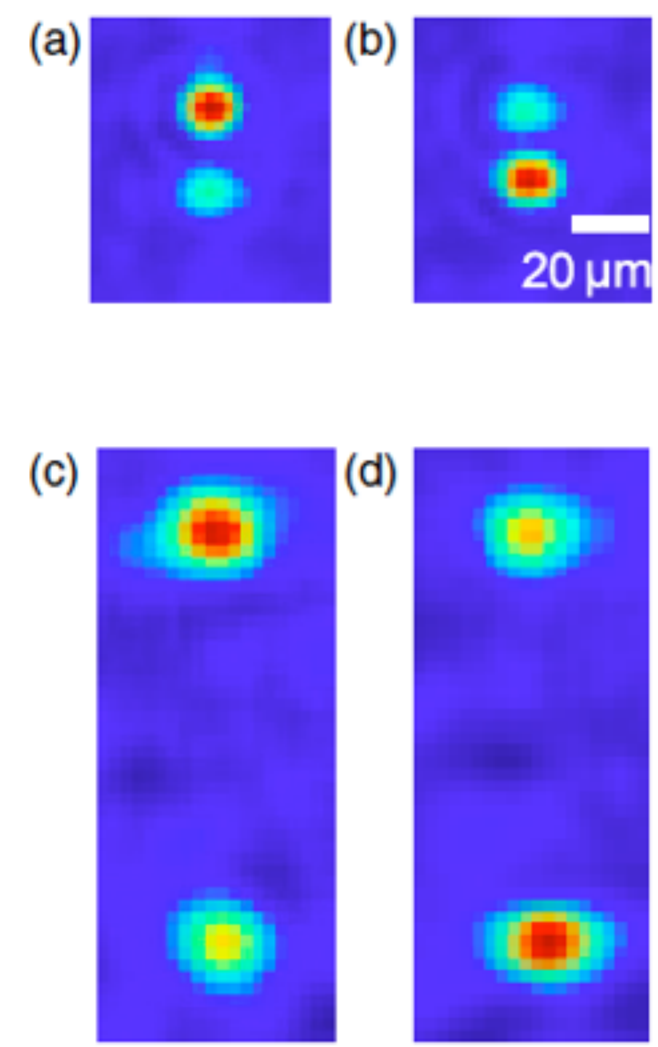
- Large momentum transfer splitters (increase *nk*)
- Large scale AI (increase *T*)
- High flux atomic sources (reduce quantum noise)
- Choice of atomic species
- Interferometer topology
- Squeezing

Large momentum transfer



- H. Müller et al., PRL **102**, 240403 (2009)
- S.-W. Chiow et al., PRL **107**, 130403 (2011)
- G. D. McDonald et al., PRA **88**, 053620 (2013)

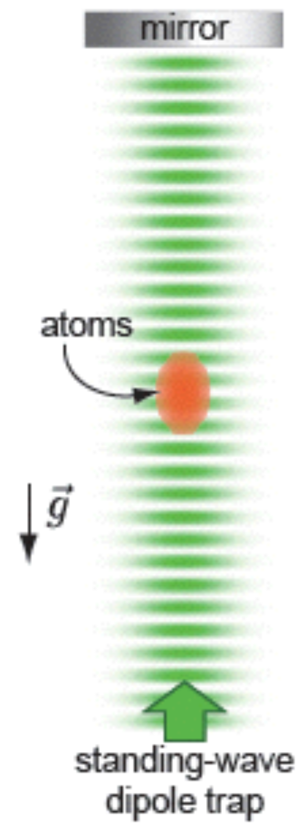


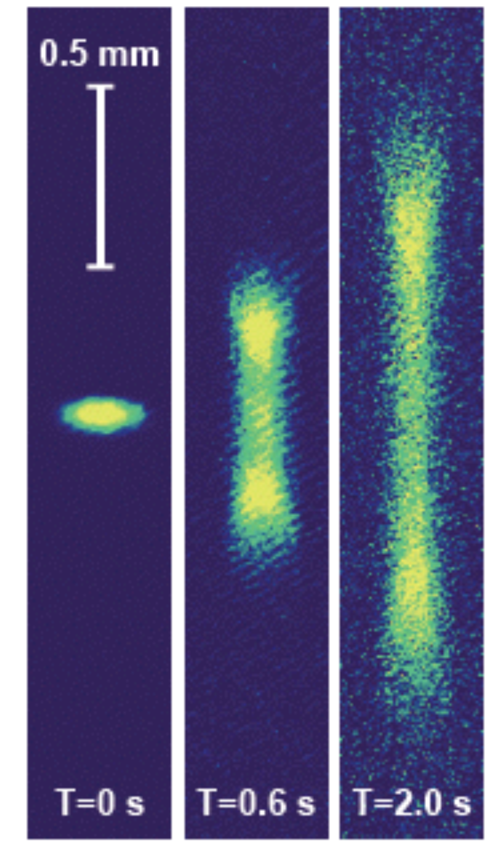


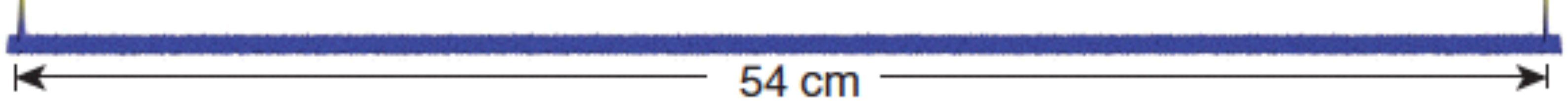
Sensitivity limits…

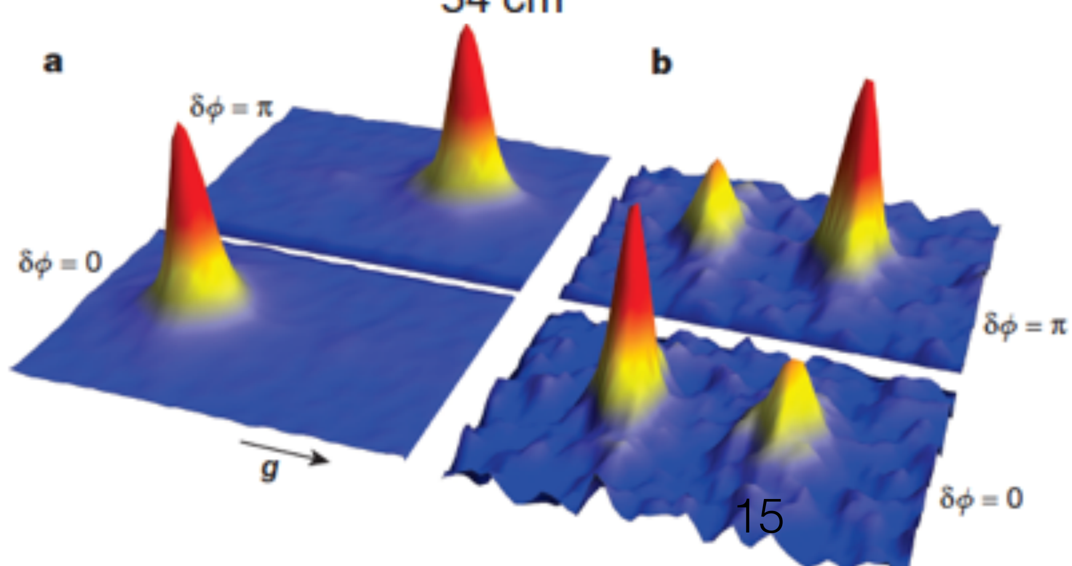
Long interaction time

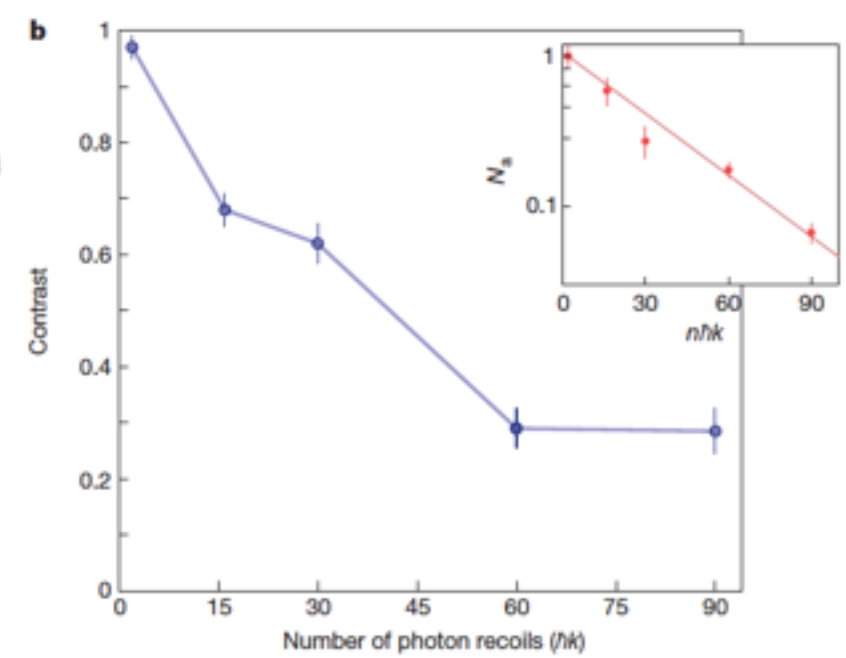
- Microgravity: in principle T>10 s
- Increasing T on Earth
  - trapped atoms (Sr)
    - up to 15000 coherent photon recoils
    - decoherence time >500 s
      - *G. Ferrari et al., PRL 97, 060402 (2006)*
      - *V. V. Ivanov et al., PRL 100, 043602 (2008)*
      - *F. Sorrentino et al., Phys. Rev. A 79, 013409 (2009)*
      - *M. Tarallo et al., PRA 86, 033615 (2012)*
  - free fall
    - requires large vertical size
    - requires very low temperatures (~nK): good for LMT splitter
    - 10 m atomic fountains already operating: Stanford, Wuhan
      - T. Kovachy et al., Nature 528, 530 (2015)
    - next future: Hannover, Firenze
    - expected differential acceleration noise ~10^{-13} g/shot





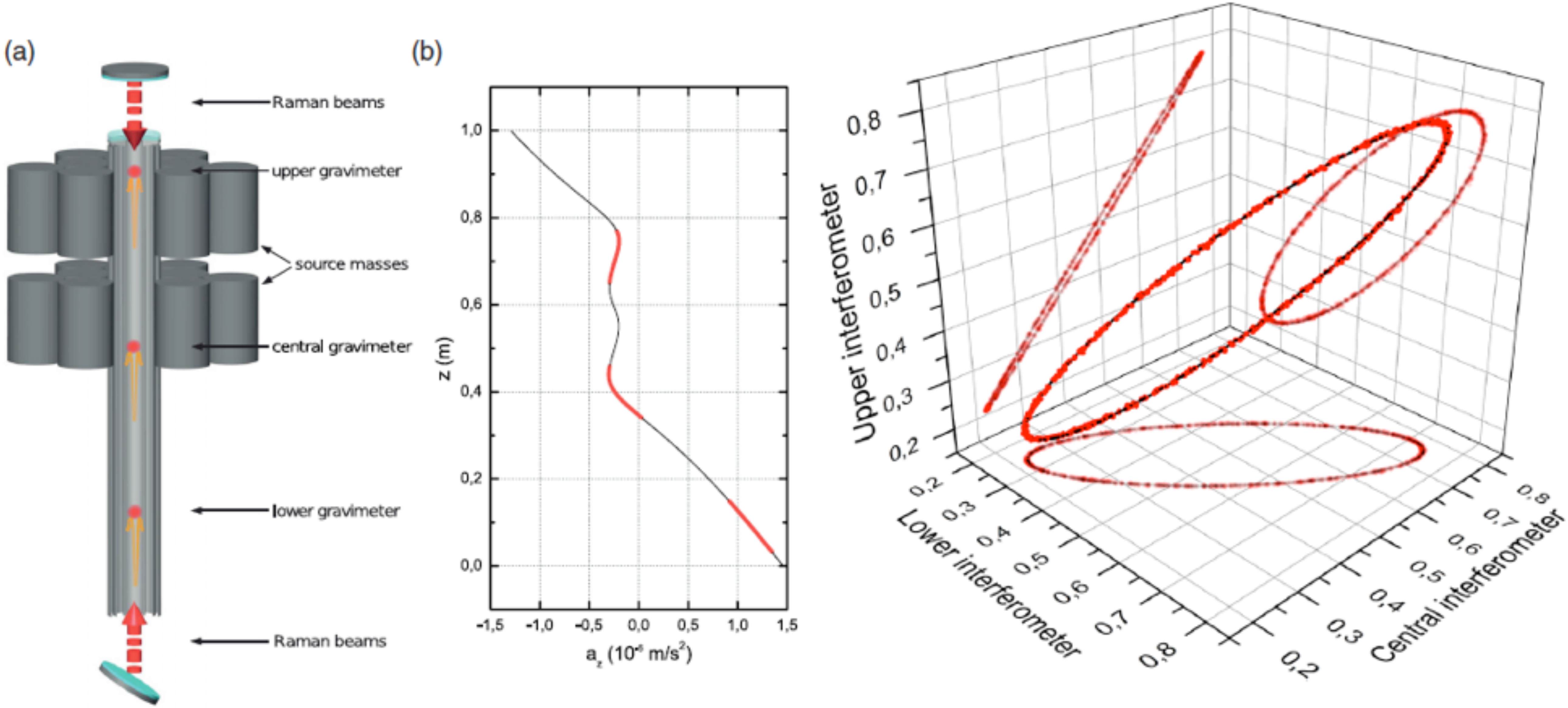






Sensitivity limits…

Multiple samples

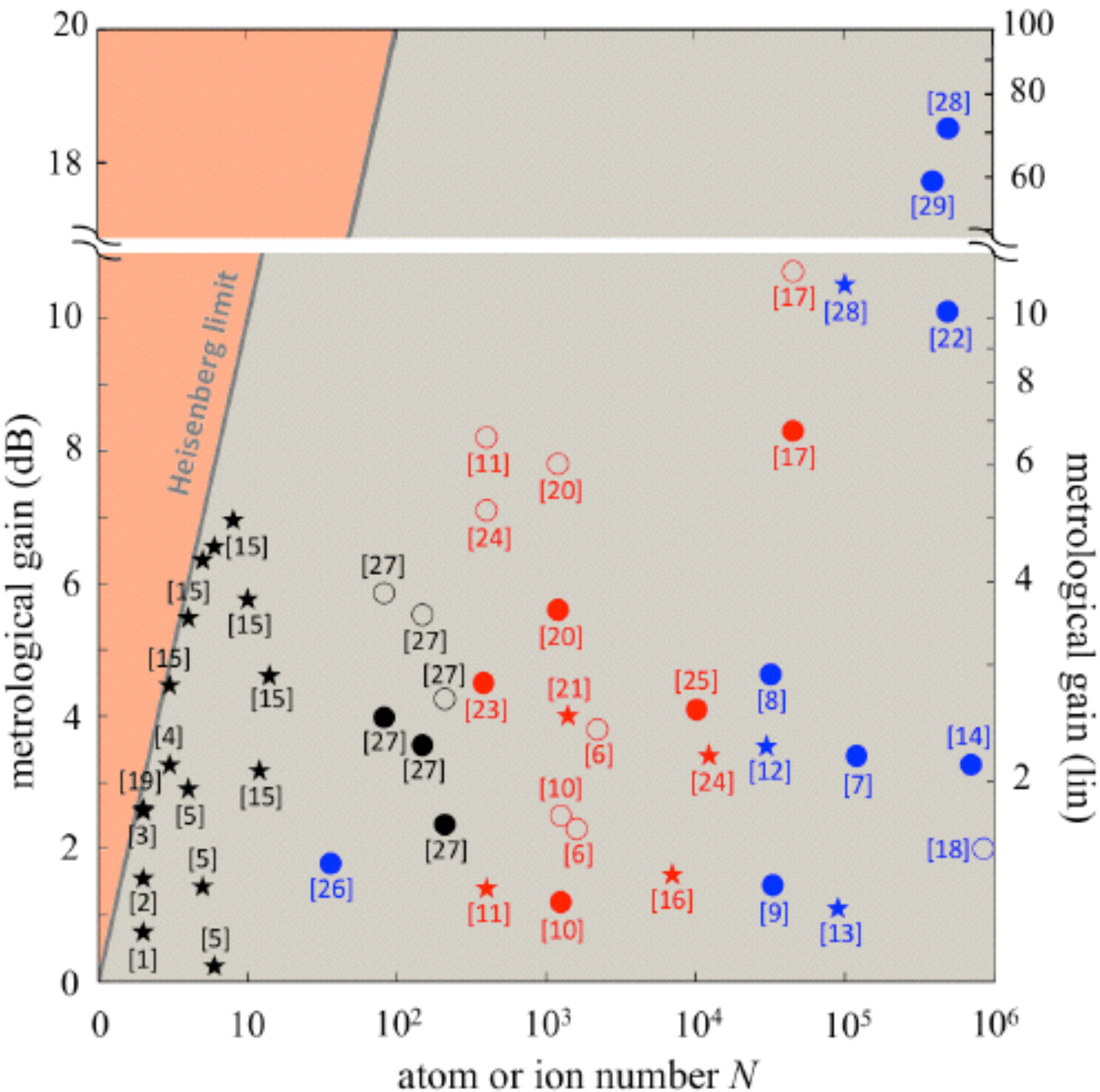


- Use three atomic clouds to measure the vertical derivative of vertical gravity gradient
  - *G. Rosi et al., Phys. Rev. Lett. 114, 013001 (2015)*
- Scalable to arbitrary large number of samples
- Simultaneous, correlated AI can improve g measurements as well
  - *F. Sorrentino et al., Appl. Phys. Lett. 101, 114104 (2012)*
- Multiple, correlated AIs to mitigate NN
  - *W. Chaibi et al, Phys. Rev. D 93, 021101 (2016)*
- See talk by S. Pelisson

Atomic species

- Most sensitive AI have been realised with alkali atoms (Rb, Cs)
  - Simple laser cooling
  - Splitter based on Raman transitions between hyperfine states -> simple detection of AI output ports
- Some interferometric schemes would work better with other species (e.g. Sr)
  - low sensitivity to stray fields
  - fast cooling to sub-μK temperatures
  - intercombination lines allow single-photon splitters to reduce the effect of laser frequency noise with long T

Squeezing



TRAPPED IONS
[1] Sackett *et al.*, 2000 NIST
[2] Meyer *et al.*, 2001 NIST
[3] Leibfried *et al.*, 2003 NIST
[4] Leibfried *et al.*, 2004 NIST
[5] Leibfried *et al.*, 2005 NIST
[15] Monz *et al.*, 2011 Innsbruck
[19] Noguchi *et al.*, 2012 Tokyo
[27] Bohnet *et al.*, 2015 NIST

BOSE-EINSTEIN CONDENSATES
[6] Esteve *et al.*, 2008 Heidelberg
[10] Reidel *et al.*, 2010 Basel
[11] Gross *et al.*, 2010 Heidelberg
[16] Lucke *et al.*, 2011 Hannover
[17] Hamley *et al.*, 2012 GeorgiaTech
[20] Berrada *et al.*, 2013 Wien
[21] Okeleon *et al.*, 2013 Basel
[23] Strobel *et al.*, 2014 Heidelberg
[24] Muessel *et al.*, 2014 Heidelberg
[25] Muessel *et al.*, 2015 Heidelberg

COLD ATOMS
[7] Appel *et al.*, 2009 Copenhagen
[8] Leroux *et al.*, 2010a MIT
[9] Schleier-Smith *et al.*, 2010 MIT
[12] Leroux *et al.*, 2010b MIT
[13] Louchet-Chauvet *et al.*, 2010 Copenhagen
[14] Chen *et al.*, 2011 JILA
[18] Sewell *et al.*, 2012 ICFO
[22] Bohnet *et al.*, 2014 JILA
[26] Barontini *et al.*, 2015 ENS
[28] Hosten *et al.*, 2016 Stanford
[29] Cox *et al.*, 2016 JILA

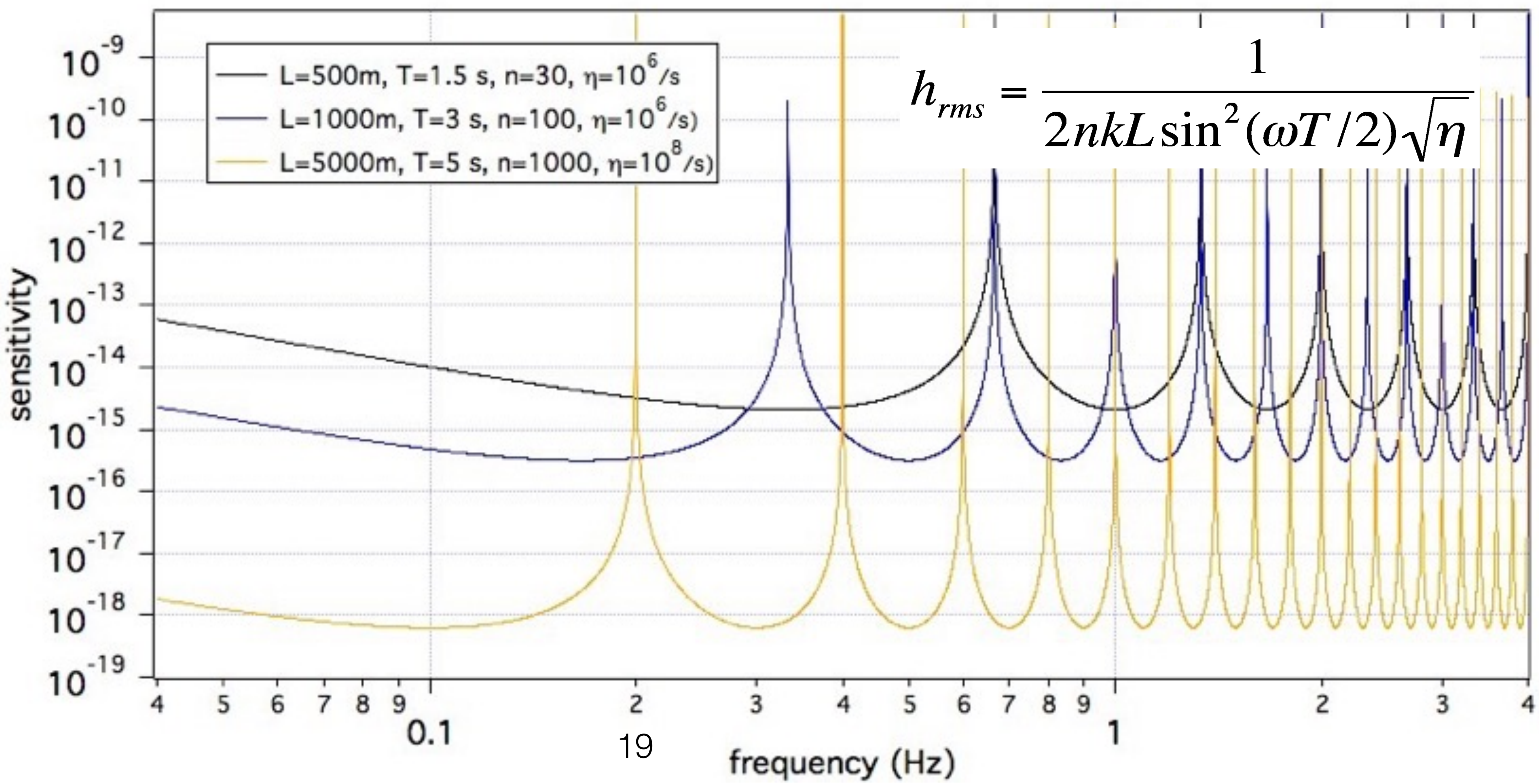
L. Pezzé et al., to be published

Summary

- Differential acceleration sensitivity of a ~10 m size vertical gradiometer
  - interaction time *T*
  - *n* photon recoils
  - 10^6 atoms at QPN
- *n*=30, T=1.5 s -> $6x10^{-13}$ g
- *n*=100, T=3 s -> $4x10^{-14}$ g

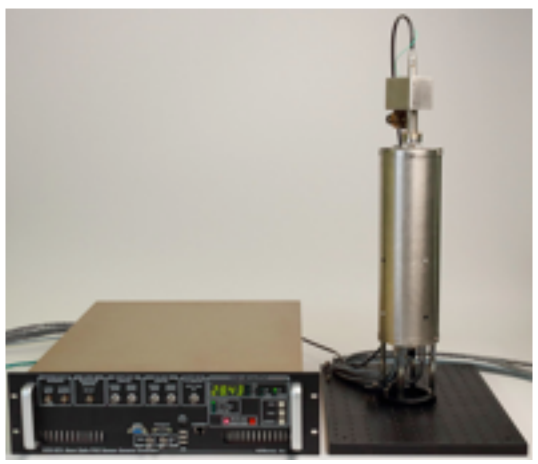
- Vertical strainmeter made of two samples with separation *L*

$$h_{rms} = \frac{1}{2nkL\sin^2(\omega T/2)\sqrt{\eta}}$$

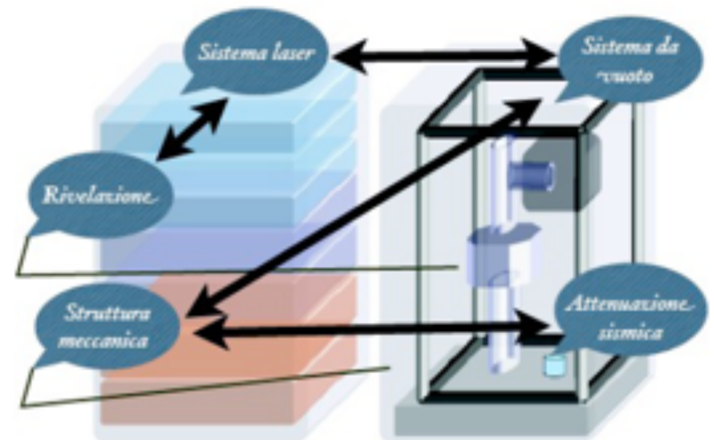


Technology readiness

- Commercial atomic gravimeters & gradiometers
    - MuQuans (France)
    - AOSense (USA)
    - AtomSensors (Italy)



AOSense

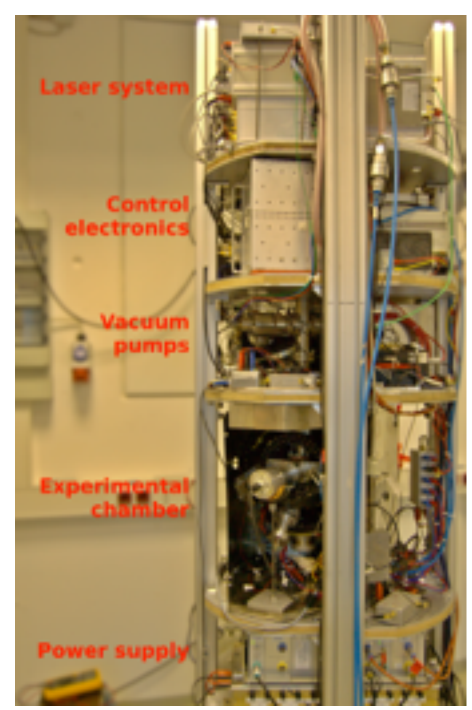


AtomSensors

µQUANS

- Prototypes for microgravity
    - I.C.E. (CNES)
    - QUANTUS/MAIUS (DLR)
    - S.A.I. (ESA)

G. Tino et al., Precision Gravity Tests with Atom Interferometry in Space, Nuclear Physics B 243, 203 (2013)



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Thank you